A HIGH RESOLUTION FLYING MAGNETIC DISK RECORDING SYSTEM WITH ZERO REPRODUCE SPACING LOSS

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Abstract - A novel method has been developed for reducing the reproduce spacing loss and thereby potentially allowing increased linear densities on a disc media while maintaining a reasonable flying height. A laminated magnetic recording media is composed of a high coercivity layer in which the data signals are stored and a thin, low coercivity, high permeability, overlayer which is called a keeper layer. A small DC bias applied to the head saturates a section of the keeper layer forming a virtual gap that is in direct contact with the high coercivity storage layer. This virtual gap functions as a transducing zone that enables a signal flux to be transferred from unsaturated keeper regions to the pole pieces of the flying head. Experimental results show that a considerable reduction, if not elimination of the reproduce spacing loss is achieved using the keepered disc. Additionally the keepered disc virtual gap was found to be about 10% smaller than the physical gap in the flying head that induced it. A series of simulations were conducted using finite difference models which confirmed the trends observed in the experimental data.

THEORY OF OPERATION

Fig. 1 shows a schematic representation of the system and its basic component parts: a laminated magnetic disc, a record/reproduce head, a record amplifier, a reproduce amplifier, and a DC bias current source which is applied to the head in the reproduce mode. The recording media is composed of a substrate layer, a high coercivity storage layer and a thin low coercivity, high permeability, overlaying layer which will be referred to as the keeper layer. The keeper layer material is a NI-Fe alloy (e.g. permalloy).

Fig. 2a shows a detail of the gap region of the flying head with a conventional recording media without the keeper layer. In the playback mode, a portion of the signal flux (indicated by the dashed lines) from a given magnetic transition links to the flux path established by the magnetic head core. The remainder of the flux is shunted along the flux leakage path to the adjacent magnetic transitions and thus not contributing to the heads output signal. The amount of leakage flux not coupling to the head is strongly effected by the head/media separation.

Fig. 2b shows a detail of the same head gap region with the keepered media and the playback bias equal to zero. The entire flux from a given magnetic transition will be shunted by the keeper layer because of the low reluctance, high permeability path; thus no flux reaches the head and no playback of the recorded signals can occur.

Fig. 2c shows what occurs when an appropriate bias field (bias not equal to 0) is created in the head core by passing a bias current through the head winding. The resulting flux from the physical gap of the head saturates a section of the keeper layer below the physical gap. The permeability of the saturated zone is approximately equal to air while the adjacent unsaturated regions are relatively high permeability. In effect the saturated zone defines a virtual gap in the keeper with a high reluctance path to the signal flux.
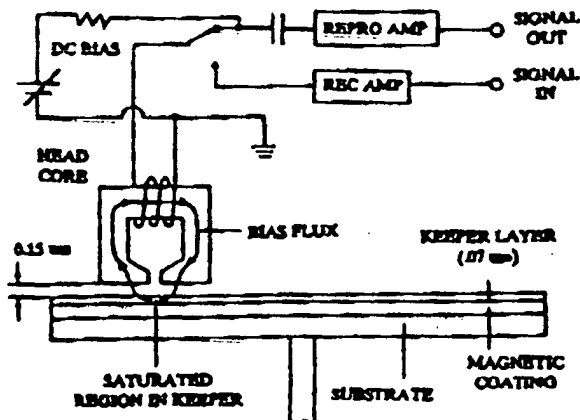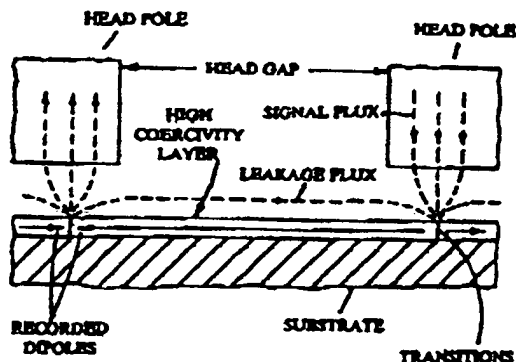

Fig. 2a. Conventional magnetic recording media without keeper.

Fig. 1. Keepered disc system diagram.
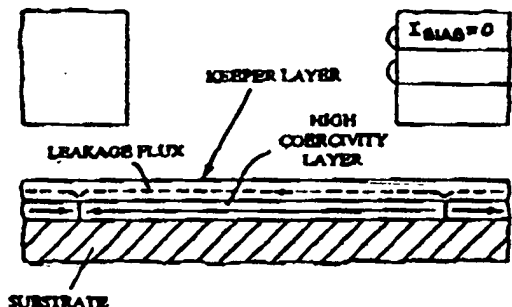

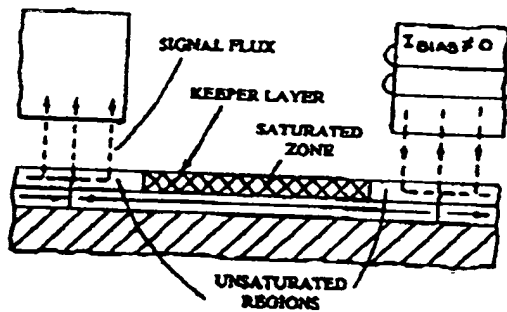Fig. 2b. Magnetic recording media with keeper layer (bias = 0).

Fig. 2c. Magnetic recording media with keeper layer (bias < > 0).

The adjacent high permeability regions extend the entire length of each head pole; thus the reluctance between the head poles and the unsaturated regions of the keeper is relatively low. This section of the keeper in which the virtual gap is formed is in effect an extension of the flying head and becomes part of that head's core structure. The signal flux from the storage layer is no longer shunted by the keeper, but instead, directed to the flying head's pole pieces through the unsaturated keeper regions. Since the unsaturated keeper regions are in direct contact with the storage layer, the physical spacing between the new head structure and the storage layer is eliminated.

The magnitude of the bias flux required to saturate the keeper will depend upon the magnetic characteristics of the material forming the keeper layer and the keeper thickness. The material characteristics and the thickness of the keeper are selected relative to the magnetic characteristics and thickness of the high coercivity layer such that the bias flux required to saturate the keeper layer and form the virtual gap is less than the flux required to undesirably alter the signals recorded in the high coercivity layer. It is also preferable that the keeper layer B-H loop have a sharp saturation transition to facilitate well defined boundaries between the saturated zone and adjacent unsaturated regions.

In the record mode, the magnitude of the record current required to optimize the high coercivity layer is much larger than the value required to saturate the low coercivity keeper, thus the keeper is rendered transparent to the recording, leaving the record head spaced away from the storage layer by the thickness of the keeper plus the flying height. This additional spacing during recording will slightly degrade the system's recording performance.

Another possible configuration of the keepered recording media is to place the keeper layer under the high coercivity layer. The advantages of this approach is that the record spacing loss is not degraded by the presence of a keeper, while maintaining the enhanced reproduce properties of a keepered disc.

While fig. 1 utilizes a DC bias to establish the saturated zone in the keeper, the bias can be established various ways. For example, a permanent magnet can be employed to interact with the magnetic core of the head and effect the localized saturation of the keeper layer needed to form the virtual gap. An AC current source may be employed as well. The AC current source

frequency should be significantly higher than the information signals. If AC bias is used, it may be necessary to use an AC filter to prevent unwanted bias-generated signals from being coupled into the reproduce circuitry.

SATURATED KEEPER MODELLING

A series of simulations were conducted using a scalar potential finite difference model with a 0.05 micrometer grid size, fig. 3. A twenty by twenty mesh was used to cover the half-space modelled. The following parameters were assumed: flying height = 0.15 micrometers, gaplength = 0.55 micrometers, keeper thickness = 0.05 micrometers. The keeper was assumed to have an unsaturated relative permeability of 1000 for flux densities less than 10,000 Gauss. The recording medium is 0.05 micrometers thick with coercivity of 400 Oersteds. The relative small-signal permeability of the recording medium as well as that of the saturated keeper is assumed to be unity. The open boundaries were assumed to have zero permeability while the boundary on the head surface was assumed to have infinite permeability. To better model the effect of the keeper layer, it's extension beyond the boundary was modelled as a two-dimensional transmission line and thus terminated with a characteristic reluctance to the pole face of:

$$\text{Keeper Termination} = (\mu \cdot \tau / d)^{1/2}$$

Where: μ = Permeability.
τ = Keeper thickness.
d = Flying height.

The grid is extended into the gap by one unit below the surface of the poles where it is terminated on a uniform potential drop representing the deep gap field. While the relative coarse and localized grid may lead to some inaccuracy, the model appears to capture the essential behavior of the reproduce process.
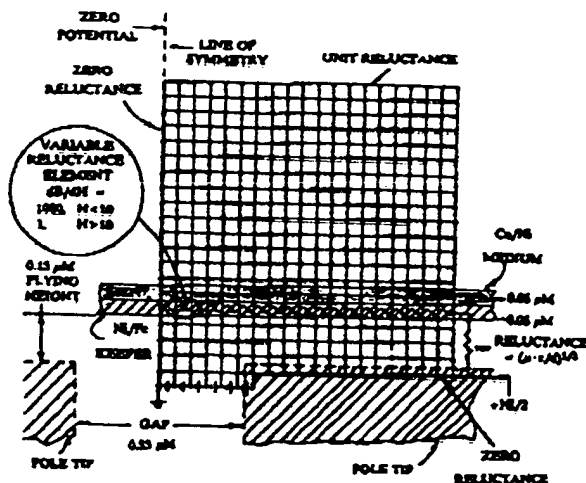

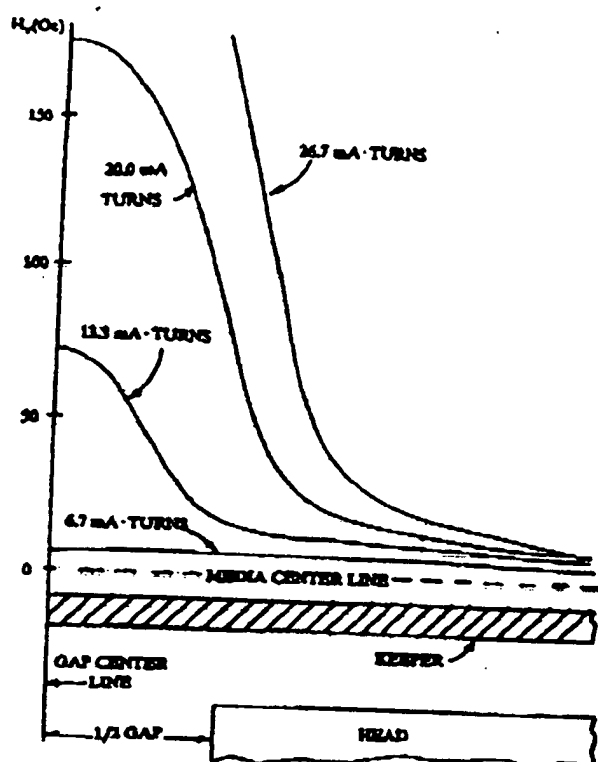Fig. 3. Illustrating finite difference modelling.

Fig. 4. Longitudinal field at center of recording medium with bias as a parameter (low bias currents).

Fig. 5. Longitudinal field at center of recording medium with write current as a parameter (high write currents).

Fig. 4 shows the field at the center of the recording medium as the DC head current increases. At very low currents very little of the fringing field penetrates the unsaturated keeper layer. At 11 mA·turns the keeper first becomes saturated at the center of the gap. As the current is increased beyond this point, the field above the gap increases rapidly and extends further from the gap. At greater distances from the gap where the keeper layer remains unsaturated, the field remains very small. At much larger currents, as might be encountered during writing, the fields increasingly resemble those that would exist in the absence of the keeper layer, fig. 5.

Small-signal reciprocity is used to gauge the reproduce response. Fig. 6 shows dH_x/dI derived from the above results. The relative square, sharp sensitivity functions correspond closely with the width of the saturated region or "virtual gap" formed in the keeper layer. Such high resolution sensitivity functions are typically seen much closer to the head gap.

In order to verify the reciprocity principle in this application an isolated magnetic charge is scanned along the centerline of the medium and its effect on the total flux entering the pole face is examined. The derivative of the flux with respect to the position of the charge maps out the sensitivity function of the head. Because only the half space is modelled, there is by implication an image charge being scanned in the opposite direction. For this reason the sensitivity function thus derived is halved in
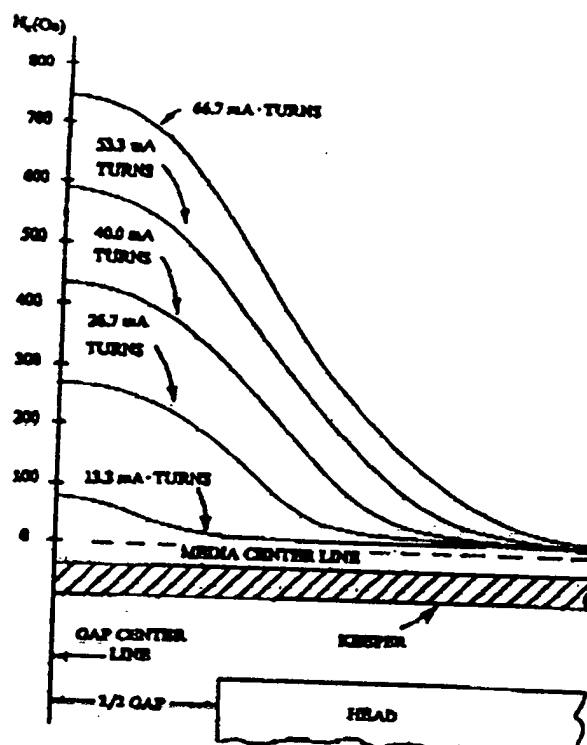
magnitude. Fig. 7 shows the results of this procedure at a bias current of 20 mA. These results are comparable on an absolute basis with the corresponding 20 mA contour from fig. 6 and are seen to be in agreement. In order to achieve sufficient numerical accuracy it was necessary to increase the flux source to one third of the saturation flux of the keeper layer. This does have an dynamic effect on the width of the saturated zone and tends to blur the sharp corner evident in the sensitivity function derived by reciprocity. It is likely that the sensitivity function obtained by reciprocity has a lower sensitivity than that obtained directly, due to numerical inaccuracies in the model. Most significantly, however, both contours have much higher resolution than the normal sensitivity function at this distance from the head (also shown).

Fig. 8 shows the Fourier transform of the sensitivity functions plotted in fig. 6. The bandwidth/resolution of the reproduce function is strongly dependent on the bias current used.

This modelling confirmed several of the phenomena observed experimentally. At very low bias currents the keeper remains highly permeable and there is little measurable output. At moderate bias currents a narrow saturated region appears in the keeper and the playback response exhibits reduced spacing loss and shorted gap null. Significant increases in short-wavelength output are indicated. The gap nullmoves to longer wavelengths as the bias current increases. At higher currents typical of writing, the keeper becomes
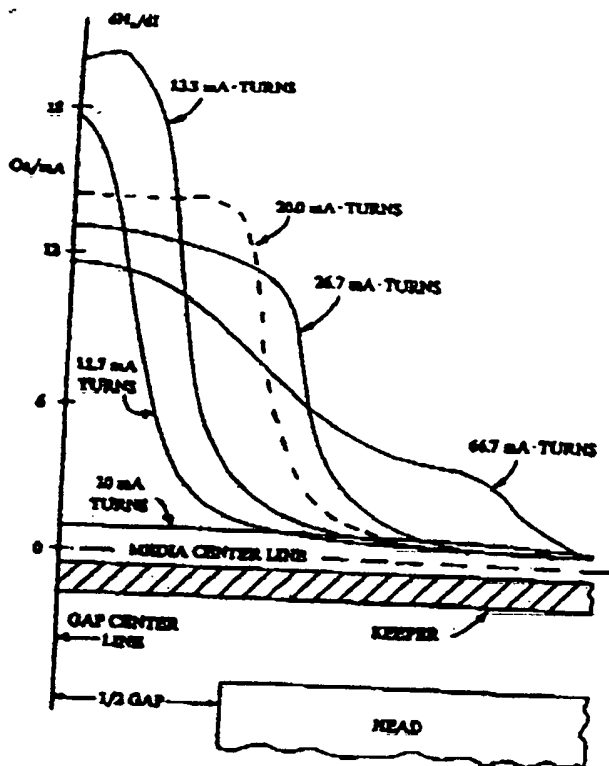
Fig. 6. Small-signal head sensitivity function, dH_x/dI, from above; write current as parameter.
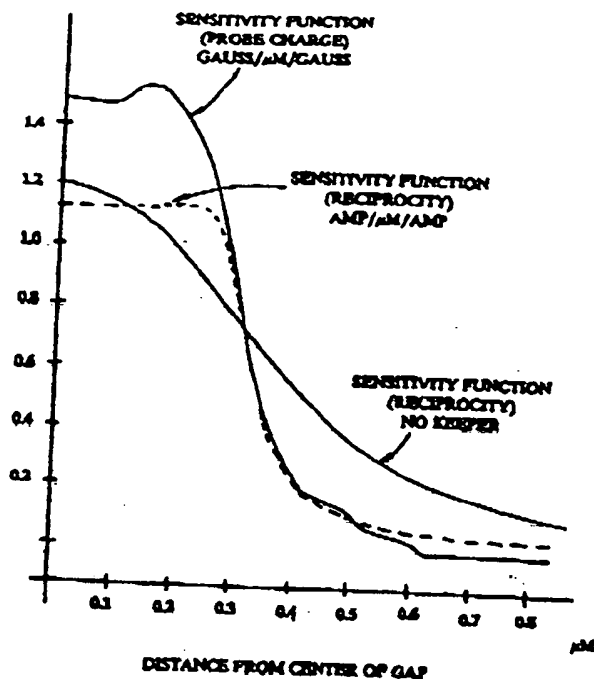

Fig. 7. Small-signal head sensitivity function obtained by scanning a small magnetic charge along the centerline of the medium ($I_b = 20$ mA-turns). Also shown: Sensitivity function obtained by reciprocity from fig. 8, and sensitivity function with keeper absent.

Fig. 8. Spectral response obtained from the Fourier transforms of fig. 6.

heavily saturated in the region of the gap. The writing process was not actually modelled but it can be seen that the form of the write field is not substantially altered from the unkeepered case.

MEDIA PREPARATION

The laminated media was prepared by a combined process of plating and sputtering. Permalloy, with a composition of 80% Ni, 20% Fe, was used as the soft, low coercivity keeper magnetic film. The high coercivity layer was an electroless plated media (standard Ampex Alar™ process), consisting of a nickle underlayer and Co/Ni magnetic layer. The media was not overcoated before sputtering the permalloy keeper layer. A Perkin Elmer 2400 RF diode sputtering system was used to sputter the permalloy keeper layer. Before sputtering, the high coercivity surface was lightly sputter etched and heated to about 100°C to remove any absorbed moisture. The sputtering parameters are shown in table 1.

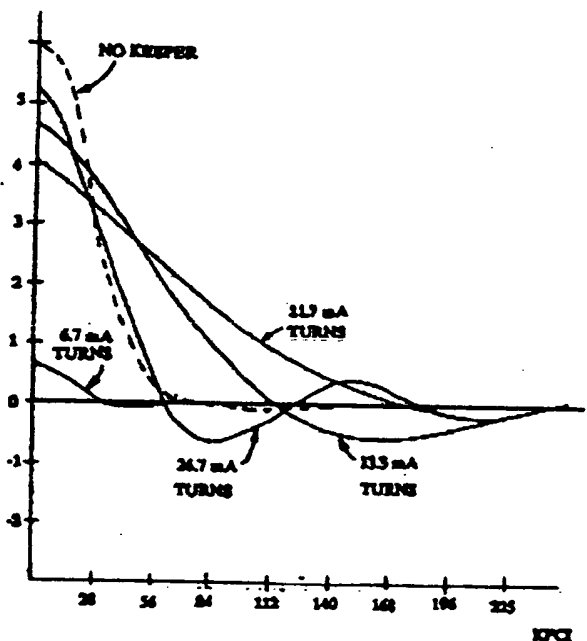|	
Ar pressure	3 millitorr
Power	1000 watts
Sub/tgt distance	2 inches(5.08 cm)
Target diameter	8 inches(20.32 cm)

Table 1. Media sputtering parameters.

In order to isolate the magnetic properties of the permalloy film, samples were sputtered on glass substrates to the same thickness as on the disc and measured on a B-H looper. The DC permeability of the film was about 3000 and the coercivity was between .5 and 1.5 Oe depending on the thickness. A typical B-H loop is shown in fig. 9. The film had very high squareness in the easy axis.
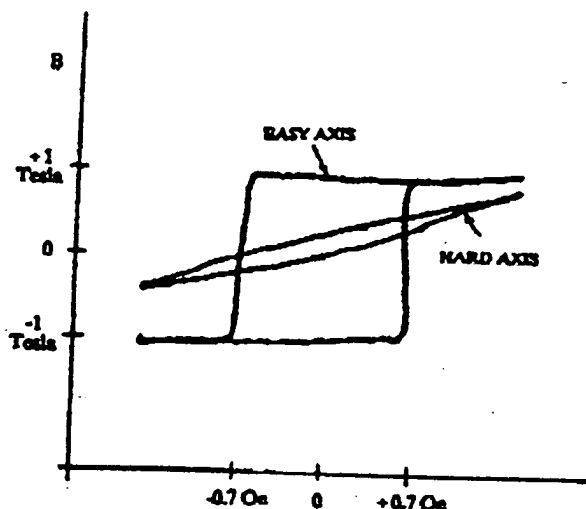

Fig. 9. B-H loop for 4 μ-in. (0.1 μm.) thick permalloy sample.

EXPERIMENTAL RESULTS

All tests were done on an in-house developed variable speed spin stand capable of measuring read/write responses, track profiles and flying height evaluations using white light interferometry techniques. The system's electronics were calibrated and flat over the frequencies of interest.

The head used was a standard three rail composite Winchester style disc head. The disc used was sputtered with a 2.8 microinch (0.07 μm.) thick keeper layer on one side only. This allowed a controlled comparison between sides with and without a keeper during tests. Table 2 gives the specifications of the head and media used for these experiments.

Head:		
Trackwidth		1.3 mils/32.5 μm.
Turns		10
Gap length		33.6 μ-in./0.84 μm.
Efficiency		0.65
Media: H_c		700 Oe
B_r		10K Gauss/1 Tesla
Coating thickness		2.4 μ-in./0.06 μm.
Keeper thickness		2.8 μ-in./0.07 μm.

Table 2. Head and media characteristics.

A flying height of approximentally 6 microinches (0.15 μm.) was used for these tests which corresponded to a head to disc speed of 500 ips (12.5 m/sec) for the head used. Higher flying heights were tested but performance gains were not as large, indicating that the system may require different keeper characteristics to optimize performance at other flying heights. Record levels in both cases were optimized for maximum output at a linear density of 50 kfci (2.0 kbits/mm). To playback a recording on the keepered disc a DC bias was introduced and also optimized to give best output at 50 kfci. The actual record levels were 11 and 12 milliamperes for the unkeepered and keepered discs respectively, the slightly larger current for the keepered disc is probably due to the greater head/media separation during record from the addition of the keeper layer. The optimized bias level for this system was 2.5 milliamperes.

Signal spectra was measured to 100 kfci (4.0 kbits/mm) using constant current square waves, the results of which for both keepered and unkeepered disc's are shown in fig. 10. The null's in both spectra responses are due to the classical reproduce gap loss function. Note that the keepered disc's null occurs at about 10% shorter wavelength than the unkeepered disc's. This corresponds to a virtual reproduce gap length of about 29.4 microinches (0.73 μm) Vs. 33.6 microinches (0.84 μm) for the unkeepered disc. It is also seen that the maximum output of the spectra with the keeper is 1.5-2 dB lower than the unkeepered disc's. This is likely due to coupling efficiencies between the flying head and the keeper. The third feature of this data is that the longest wavelength output of the unkeepered disc seems to be lower than the keepered disc despite its presumed higher efficiency. Since track profiles of both recordings showed no significant differences this may be an artifact.

Fig. 11 show the previously measured data corrected for the gap loss function. As can be seen the effective record/play spacing losses have been considerably reduced by the presence of the keeper.
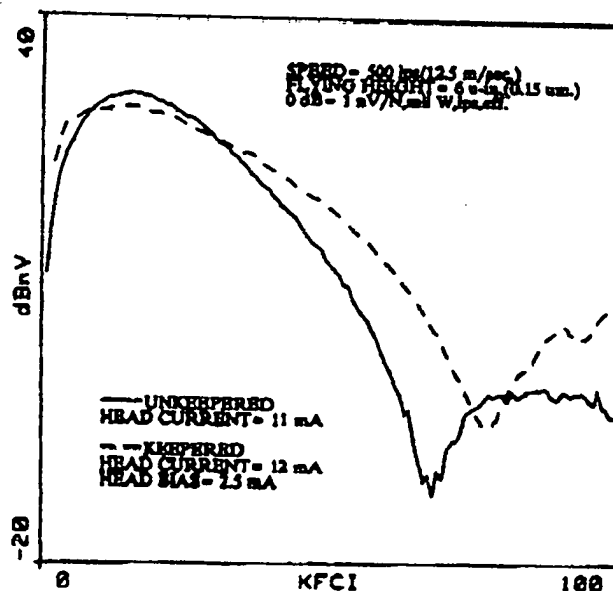

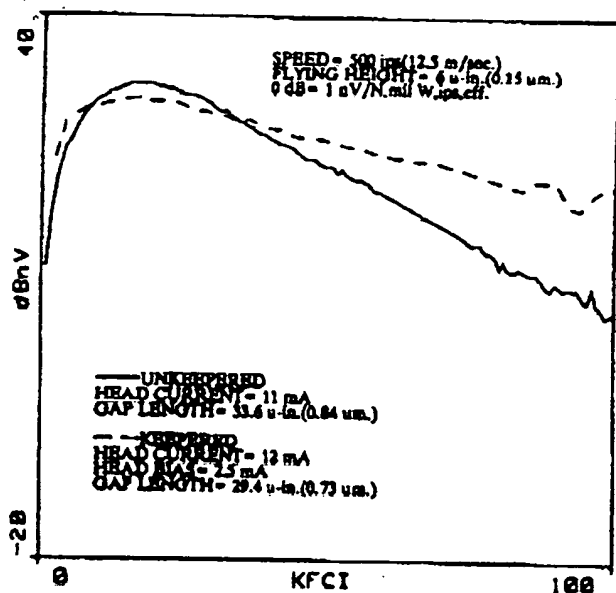Fig. 10. Raw signal spectra for both keepered and unkeepered discs.

Fig. 11. Gap loss corrected spectra for keepered and unkeepered discs.

Parameter	Unkeepered disk (μ-in./μm)	Keepered disk (μ-in./μm)
Measured a+d	15.05/0.376	8.81/0.220
Measured d	6/0.15	8.8/0.22
Calculated a	8.86/0.222	10.45/0.261
Effective d	6.19/0.155	-1.64/-0.041

Table 3. Measured and calculated spacings.

When the data is further corrected for thickness losses the slope of the data can be used to derive a number corresponding to the reproduce flying height plus an effective recorded transition width. Using the known recording parameters a record transition width may be calculated using the Williams-Comstock model[1] with the following relationship:

$$a = 2 \cdot (M_r/H_c \cdot \delta \cdot (d + \delta/2))^{1/2}$$

Where:
- a = Recorded transition length.
- M_r = Remenent magnetization of media.
- H_c = Remenent coercivity of media.
- δ = Media storage layer thickness.
- d = Spacing between head and storage layer.

Note that the spacing parameter d for the keepered disc is larger due to this particular implementation, which has the keeper layer on top of the storage layer. Placing the keeper layer under the storage layer may work equally well in playback and avoid the additional spacing during recording. By using the measured total spacing loss and subtracting the calculated transition width a value for the effective reproduce spacing can be attained. Table 3 gives the results of both the measured and calculated parameters for both discs.

It is seen that the resulting effective reproduce spacing for the unkeepered disc is very close to the measurement based on interferometry, but the keepered disc's effective spacing is actually slightly negative! This negative spacing implies either a tolerance build up in the measurements or that an additional unidentified effect is occurring which decreases the effective spectra slope.

CONCLUSIONS

A novel means of reducing, if not eliminating, the reproduce spacing loss and an effective reduction in the reproduce gap length of a flying head has been demonstrated. Subjects for further investigation include:

1. Optimization of keeper thickness and magnetics for best signal response.
2. Characterization of possible noise and distortion from use of bias and keeper layer.
3. Explore use of keeper as underlayer.
4. Study keeper use on vertical media.

It is felt that keepered disc systems may hold the promise of significantly increasing recording densities without the reliability penalties of decreased flying heights.

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